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Fuzzy Sliding Mode Decoupling Controller Design Based on Indirect Field Orientation for Induction Motor Drive

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Abstract – In this paper, the design of a speed control scheme based on total fuzzy-sliding mode control for indirect field-orientated induction motor (IM) is proposed. In this scheme, the motor speed is controlled by fuzzy sliding mode controller, in which the fuzzy logic controller replaces the discontinuous part of the classical SMC law ($k \cdot sign(s)$). The proposed fuzzy sliding mode control operation can reduce the dependence on the motor parameters and disturbance uncertainties. The decoupling scheme uses two fuzzy sliding mode controllers to regulate the *d*-axis and q-*axis* stator currents respectively. This new current controller exhibits several advantages such as fast dynamic response, perfect decoupling and robustness to parameter variations. Finally, the effectiveness of the complete proposed control scheme is verified by numerical simulation. The numerical validation results of the proposed scheme have presented good performances compared to the classical sliding mode control.

Keywords: induction motor, vector control, decoupling, sliding mode control and fuzzy sliding mode.

I. INTRODUCTION

Nowadays, like a consequence of the important progress in the power electronics and of micro-computing, the control of the AC electric machines known a considerable development and a possibility of the real time implantation applications. AC motors, especially, the induction motor (IM), enjoy several inherent advantages, like simplicity, reliability, low cost, and almost maintenance-free electrical drives [1]. However, for high dynamic performance industrial applications, their control remains a challenging problem because they exhibit significant nonlinearities, and many of the parameters, mainly the rotor resistance, vary with the operating conditions. On the other hand and during numerous decades, the machine with direct current (DC) machine constituted the only electromechanical source of variable speed applications because of its ease of control, where torque and flux are naturally decoupled and can be controlled independently by the torque producing current and the flux producing current [1, 2, 3].

The field-oriented control technique has been widely used in industry for high-performance IM drive [2, 3], where the knowledge of synchronous angular velocity is often necessary in the phase transformation for achieving the favourable decoupling control between motor torque and rotor flux as for a separately excited DC machine. This control strategy can provide the same performance as achieved from a separately excited DC machine [3, 4]. This technique can be performed by two basic methods: direct vector control and indirect vector control. Both DFO and IFO solutions have been implemented in industrial drives demonstrating performances suitable for a wide spectrum of technological applications. This stimulated a significant research activity to develop IM vector control algorithms using nonlinear control theory in order to improve performances, achieving speed (or torque) and flux tracking, or to give a theoretical justification of the existing solutions [2, 3]. Sliding mode control theory, due to its order reduction, disturbance rejection, strong robustness and simple implementation by means of power converter, is one of the prospective control methodologies for electrical machines[5, 6]. The feature of sliding mode control system is that the controller is switched between tow distinct control structures. In general, the design of variable structure controller generally consists of two steps, which are hitting and sliding phases [5]. First, the system is directed towards a switching surface by a feedback control law, the sliding mode occurs. When the system states enter the sliding mode, the dynamic of the system are determined by the choice of sliding surface. The mentioned situations are independent of parametric uncertainties and load disturbances. Hence, SMC has been employed to the position and speed control of AC machines. But because of the non-continuous switch feature of SMC, the chattering can occur in the control system [5, 6]. In order to reduce or overcome the system chattering, researches have proposed the fuzzy control design methods based on the sliding-mode control scheme [7, 8, 9]. These controllers are referred to as fuzzy sliding-mode controllers (FSMC).

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Since only one variable is defined as the fuzzy input variable, the main advantage of the FSMC system is that the fuzzy rules can be reduced.

In this paper, a fuzzy sliding mode decoupling controller which combines the merits of the sliding mode control and the fuzzy inference mechanism is proposed. In addition, an outer-loop speed controller that employs fuzzy sliding mode control is derived. In this scheme, a fuzzy sliding mode controllers are investigated, in which the fuzzy logic system is used to replace the discontinuous control action ($k \cdot sign(s)$) of the classical SMC law. The reminder of this paper is organized as follows. Section II reviews the principle of the indirect field-oriented control (FOC) of induction motor. Section III shows the development of sliding mode controllers design for IM control. The proposed fuzzy sliding mode control scheme is presented in section IV. Section V gives some simulation results. Finally, some conclusions are drawn in section VI

II. INDIRECT FIELD-ORIENTED CONTROL OF THE IM

The dynamic model of three-phase, Y-connected induction motor can be expressed in the *d-q* synchronously rotating frame as [1, 2, 3]:

$$\begin{cases} \dfrac{di_{ds}}{dt} = \dfrac{1}{\sigma.L_s}.\left(-\left(R_s + \left(\dfrac{L_m}{L_r}\right)^2.R_r\right).i_{ds} + \sigma.L_s.\omega_e.i_{qs} + \dfrac{L_m.R_r}{L_r^2}.\phi_{dr} + \dfrac{L_m}{L_r}.\phi_{qr}.\omega_r + V_{ds}\right) \\ \dfrac{di_{qs}}{dt} = \dfrac{1}{\sigma.L_s}.\left(-\sigma.L_s.\omega_e.i_{ds} - \left(R_s + \left(\dfrac{L_m}{L_r}\right)^2.R_r\right).i_{qs} - \dfrac{L_m}{L_r}.\phi_{dr}.\omega_r + \dfrac{L_m.R_r}{L_r^2}.\phi_{qr} + V_{qs}\right) \\ \dfrac{d\phi_{dr}}{dt} = \dfrac{L_m.R_r}{L_r}.i_{ds} - \dfrac{R_r}{L_r}.\phi_{dr} + (\omega_e - \omega_r)\phi_{dr} \\ \dfrac{d\phi_{qr}}{dt} = \dfrac{L_m.R_r}{L_r}.i_{qs} - (\omega_e - \omega_r)\phi_{dr} - \dfrac{R_r}{L_r}.\phi_{qr} \\ \dfrac{d\omega_r}{dt} = \dfrac{3}{2}\dfrac{P^2.L_m}{L_r.J}.(i_{qs}.\phi_{dr} - i_{ds}.\phi_{qr}) - \dfrac{f_c}{J}.\omega_r - \dfrac{P}{J}.T_l \end{cases} \quad (1)$$

Where σ is the coefficient of dispersion and is given by (2):

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \quad (2)$$

L_s, L_r, L_m stator, rotor and mutual inductances;

R_s, R_r stator and rotor resistances;

ω_e, ω_r electrical and rotor angular frequency;

ω_{sl} slip frequency $(\omega_e - \omega_r)$;

τ_r rotor time constant (L_r / R_r);

P pole pairs

The main objective of the vector control of induction motors is, as in DC machines, to independently control the torque and the flux; this is done by using a *d-q* rotating reference frame synchronously with the rotor flux space vector [2, 3]. In ideally field-oriented control, the rotor flux linkage axis is forced to align with the *d*-axes, and it follows that [3, 4, 12]:

$$\phi_{rq} = \frac{d\phi_{rq}}{dt} = 0 \quad (3)$$

$$\phi_{rd} = \phi_r = cons\tan t \quad (4)$$

Applying the result of (3) and (4), namely field-oriented control, the torque equation become analogous to the DC machine and can be described as follows:

$$T_e = \frac{3}{2}\frac{p \cdot L_m}{L_r} \cdot \phi_r \cdot i_{qs} \quad (5)$$

And the slip frequency can be given as follow:

$$\omega_{sl} = \frac{1}{\tau_r}\frac{i_{qs}^*}{i_{ds}^*} \quad (6)$$

Consequently, the dynamic equations (1) yield:

$$\frac{di_{ds}}{dt} = -\left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma\tau_r}\right)i_{ds} + \omega_e i_{qs} + \frac{L_m}{\sigma L_s L_r \tau_r}\phi_{rd} + \frac{1}{\sigma L_s}V_{ds} \quad (7)$$

$$\frac{di_{qs}}{dt} = -\left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma\tau_r}\right)i_{qs} - \omega_e i_{ds} + \frac{L_m}{\sigma L_s L_r \tau_r}\phi_{rd} + \frac{1}{\sigma L_s}V_{ds} \quad (8)$$

$$\frac{d\phi_r}{dt} = \frac{L_m}{\tau_r}i_{ds} - \frac{1}{\tau_r}\phi_{rd} \quad (9)$$

$$\frac{d\omega_r}{dt} = \frac{3}{2}\frac{P^2 L_m}{JL_r}i_{qs}\phi_{rd} - \frac{f_c}{J}\omega_r - \frac{P}{J}T_l \quad (10)$$

The decoupling control method with compensation is to choose inverter output voltages such that [10]:

$$V_{ds}^* = \left(K_p + K_i\frac{1}{s}\right)(i_{ds}^* - i_{ds}) - \omega_e \sigma L_s i_{qs}^* \quad (11)$$

$$V_{qs}^* = \left(K_p + K_i\frac{1}{s}\right)(i_{qs}^* - i_{qs}) + \omega_e \sigma L_s i_{ds}^* + \omega_r\frac{L_m}{L_r}\phi_{rd} \quad (12)$$

According to the above analysis, the indirect field-oriented control (IFOC) [1, 4, 10] of induction motor with current-regulated PWM drive system can reasonably presented by the block diagram shown in the Fig. 1.

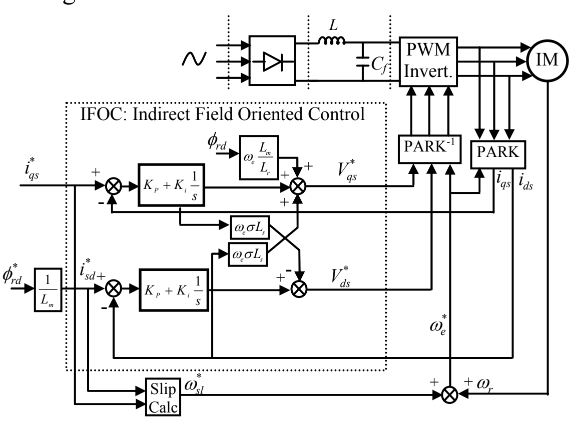

Fig. 1. Block diagram of IFOC for an induction motor.

III. SLIDING MODE CONTROL

A Sliding Mode Controller is a Variable Structure Controller (VSC). Basically, a VSC includes several different continuous functions that can map plant state to a control surface, and the switching among different functions is determined by plant state that is represented by a switching function [6, 7, 8].

Without lost of generality, consider the design of a sliding mode controller for the following second order system:

$$\ddot{x} = f(x, \dot{x}, t) + b \cdot u(t) \tag{13}$$

Here we assume $b > 0$. $u(t)$ is the input to the system. The following is a possible choice of the structure of a sliding mode controller [5, 11]:

$$u = u_{eq} + k \cdot sign(s) \tag{14}$$

Where u_{eq} is called equivalent control which dictates the motion of the state trajectory along the sliding surface [9]. is a constant, representing the maximum controller output. s is called switching function because the control action switches its sign on the two sides of the switching surface $s = 0$. For a second order system S is defined as [11, 12]:

$$s = \dot{e} + \lambda e \tag{15}$$

Where $e = x_d - x$ and x_d is the desired state. λ is a constant. $sign(s)$ is a *sign* function, which is defined as:

$$sign(s) = \begin{cases} -1 & s < 0 \\ 1 & s > 0 \end{cases} \tag{16}$$

The control strategy adopted here will guarantee the system trajectories move toward and stay on the sliding surface $s = 0$ from any initial condition if the following condition meets:

$$s\dot{s} \le -\eta \tag{17}$$

Where η is a positive constant that guarantees the system trajectories and hit the sliding surface in finite time [6, 9].

Using a *sign* function often causes chattering in practice. One solution is to introduce a boundary layer around the switch surface [9, 12, 13]:

$$u = u_s + u_{eq} \tag{18}$$

Where:

$$u_s = k \cdot sat\left(s/\xi \right) \tag{19}$$

Where the constant factor ξ defines the thickness of the boundary layer. $sat\left(s/\xi \right)$ is a saturation function that is defined as:

$$sat\left(s/\xi \right) = \begin{cases} sign\left(\frac{s}{\xi}\right) & \left|\frac{s}{\xi}\right| \ge 1 \\ \frac{s}{\xi} & \left|\frac{s}{\xi}\right| < 1 \end{cases} \tag{20}$$

The diagram of u_s versus s/ξ is shown in Fig. 2.

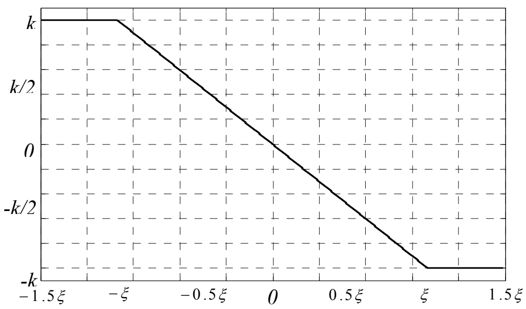

Fig. 2. The discontinuous control action of the SMC control law ($u_s = ksat(s/\xi)$)

III.1. *Design of sliding mode current controllers*

The currents loop is often the inner regulated loop in a field oriented controlled induction motor drive, and the overall performance of the drive depends strongly on the performance of current control. Therefore, a precise and fast current control is essential to achieve high static and dynamic performance for the FOC of induction motors. If the actual stator currents are not adjusted precisely and instantaneously to the reference values, cross coupling will be caused between the motor torque and rotor flux. Thus, the performance of the FOC degrades [2, 11].

In this paper, we propose a current control method based on sliding mode control design. The proposed control design uses two sliding mode controllers to regulate the *d*-axis and *q*-axis stator currents respectively. The design of the controllers consists of two steps.

Firstly, we define sliding surfaces $s = [s_1 \quad s_2] = 0$ as follows:

$$s_1 = i_{ds}^* - i_{ds} \tag{21}$$

$$s_2 = i_{qs}^* - i_{qs} \tag{22}$$

Where i_{ds}^* and i_{qs}^* are the reference values of the *d*-axis and *q*-axis stator currents, respectively. If the system stays stationary on the surface, then we can obtain $s_1 = s_2 = 0$. Substituting (21) and (22) into $s_1 = 0$ and $s_2 = 0$ yields

$$i_{ds} = i_{ds}^* \text{ and } i_{qs} = i_{qs}^* \tag{23}$$

Secondly, we design the voltage control law, which forces the system to move on the sliding surface in a finite time, as follows:

$$V_{ds}^* = V_{ds}^{equ} + k_1 \cdot sat(s_1/\xi_1) \tag{24}$$

$$V_{qs}^* = V_{qs}^{equ} + k_2 \cdot sat(s_2/\xi_2) \tag{26}$$

Where V_{ds}^{equ} and V_{qs}^{equ} are the equivalent control actions, and are defined as:

$$V_{ds}^{equ} = \sigma.L_s\left(\dot{i}_{ds}^* + \frac{1}{\sigma.L_s}\left(R_S + R_r.\left(\frac{L_m}{L_r}\right)^2\right).i_{ds} - w_e.i_{qs} - \frac{L_m.R_r}{\sigma.L_s L_r^2}\phi_r^*\right) \tag{27}$$

$$V_{qs}^{equ} = \sigma.L_s.[\dot{i}^*{}_{qs} + \omega_e.i_{ds} + \frac{1}{\sigma.L_s}\left(R_s + R_r\left(\frac{L_m}{L_r}\right)^2\right).i_{qs} + \frac{L_m}{\sigma L_s L_r}\phi_r^*\omega_r] \tag{28}$$

To verify the stability conditions, parameters k_1 and k_2 must be positives.

III.2. *Design of sliding mode speed controller*

To control the speed of the induction machine, the sliding surface is defined as follows:

$$s(\omega) = \omega_r^* - \omega_r \tag{29}$$

The derivative of the sliding surface can be given as:

$$\dot{s}(\omega_r) = \dot{\omega}_r^* - \dot{\omega}_r \tag{30}$$

Taking account the mechanical equation of the induction motor defined in the system of equations (1), the derivative of sliding surface becomes:

$$\dot{S}(\omega_r) = \dot{\omega}_r^{\ *} - \left(\frac{3}{2} \frac{P^2 L_m \phi_{dr}^*}{J L_r} . i_{qs} - \frac{f_c}{J} \dot{\omega}_r - \frac{P}{J} T_l \right) \quad (31)$$

We take

$$i_{qs} = i_{qs}^{equ} + i_{qs}^{n} \quad (32)$$

During the sliding mode and in permanent regime, we have $s(\omega_r) = 0$, $\dot{s}(\omega_r) = 0$, the equivalent control action can be defined as follows:

$$i_{qs}^{equ} = \frac{2}{3} \frac{J L_r}{P^2 L_m \phi_{dr}^*} \left(\dot{\omega}_r^* + \frac{f_c}{J} \omega_r + \frac{P}{J} T_l \right) \quad (33)$$

The discontinuous control action can be given as:

$$i_{qs}^{n} = k_{iqs} \cdot sat(s(\omega_r)/\xi_\omega) \quad (34)$$

To verify the system stability condition, the factor k_{iqs} must be positive.

IV. FUZZY SLIDING MODE CONTROL

The disadvantage of sliding mode controllers is that the discontinuous control signal produces chattering dynamics; chatter is aggravated by small time delays in the system. In order to eliminate the chattering phenomenon, different schemes have been proposed in the literature. However, this does not solve the problem completely. In this section, a fuzzy sliding surface is introduced to develop a sliding mode controller, where the expression $k \cdot sat(s/\xi)$ of all sliding mode controllers is replaced by a fuzzy system mechanism for reduce the chattering phenomenon. This approach shows that a particular fuzzy controller is an extension of an SMC with boundary layer [13].

Because the data manipulated in the fuzzy inference mechanism is based on fuzzy set theory, the associated fuzzy sets involved in the fuzzy control rules are defined as follows:

BN : Big Negative	**Bigger**
MN : Medium Negative	**Big**
ZE : Zero	**Medium**
MP : Medium Positive	**Small**
BP : Big Positive	**Smaller**

Since only five fuzzy subsets, BN, MN, ZE, MP and BP, are defined for s, the fuzzy inference mechanism contains five rules for the FLC output. The resulting fuzzy inference rules for the output variable u_n are as follows:

Rule 1: **IF** s is BN **THEN** u_n is Bigger

Rule 2: **IF** s is MN **THEN** u_n is Big

Rule 3: **IF** s is ZE **THEN** u_n is Medium

Rule 4: **IF** s is MP **THEN** u_n is Small

Rule 5: **IF** s is BP **THEN** u_n is Smaller

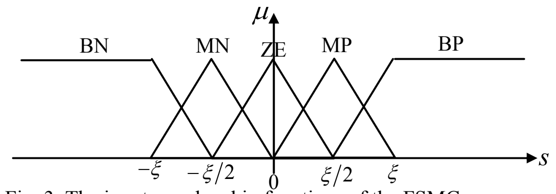

Fig. 3. The input membership functions of the FSMC

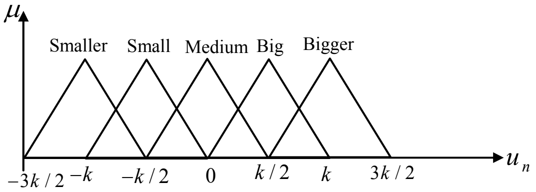

Fig. 4. The output membership function of the FSMC

Fig. 5 shows the result of a defuzzified output u_n for a fuzzy input s.

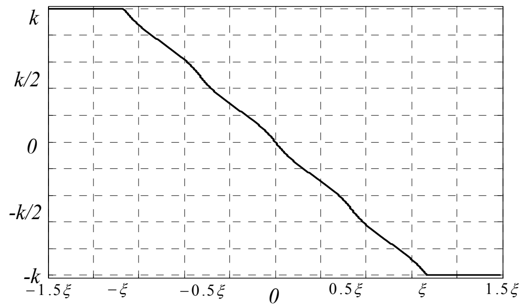

Fig. 5. The discontinuous control action of the fuzzy sliding mode controller

In order to control the speed and stator currents of the induction motor, the three discontinuous control actions of the outer- and inner-loops are replaced by fuzzy logic controllers.

The membership functions of input and output fuzzy sets are depicted in Figs. 6 and 7. In this study, the triangular membership functions and center average defuzzification method are adopted, as they are computationally simple, intuitively plausible, and most frequently used in the opening literatures

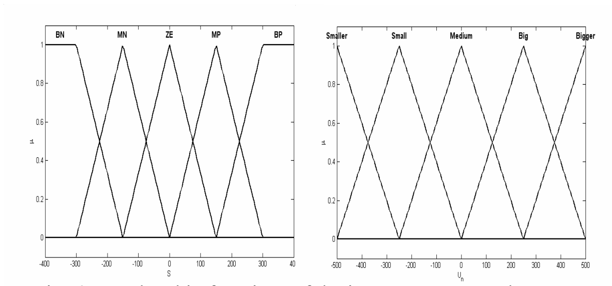

Fig. 6. Membership functions of the inputs s_1, s_2 and outputs V_{as}^n, V_{ds}^n of FSMC current controllers

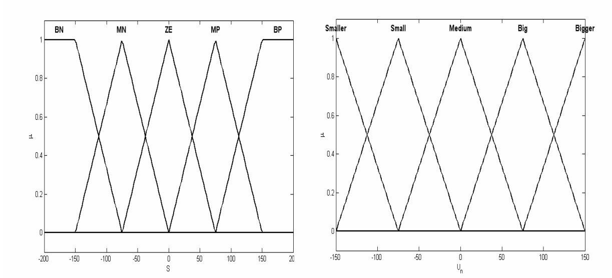

Fig. 7:.Membership functions of the input s and output i_{qs}^n FSMC speed controller.

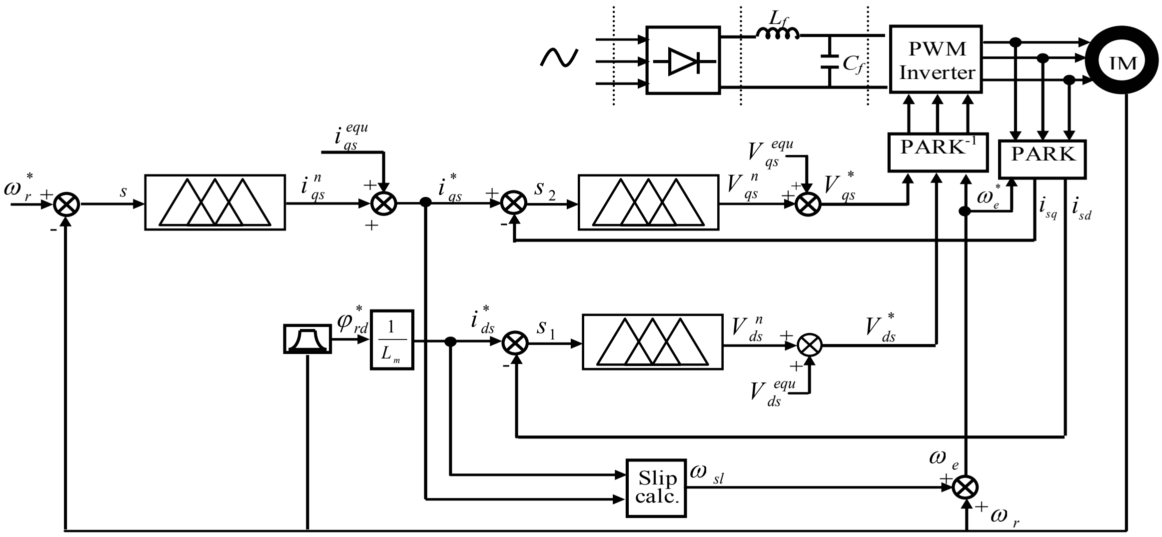

Fig. 8: The block diagram of proposed fuzzy sliding mode speed and currents control of induction motor

V. SIMULATION RESULTS

To prove the rightness and effectiveness of the proposed control scheme, we apply the designed controllers to the speed control of the induction motor. The induction motor is a three phase, *Y* connected, four pole, 1.5 kW, 1428min^{-1} 220/380V, 50Hz. The machine parameters are given in [14]. The configuration of the overall control system is shown in Fig. 08. It mainly consists of an induction motor, a ramp comparison current-controlled pulse width modulated (PWM) inverter, a slip angular speed estimator, an inverse park, indirect field oriented control bloc based on fuzzy sliding mode current controller, and an outer speed feedback control loop contains on a fuzzy sliding mode controller.

Fig. 9 shows the disturbance rejection of fuzzy sliding mode controller when the machine is operated at 200 [rad/sec] under no load and a nominal load disturbance torque (10 N.m) is suddenly applied and eliminated at 1.5sec, 2.5ec respectively, followed by a reversed reference (-200rad/sec) at 4sec. The fuzzy sliding mode controller rejects the load disturbance very rapidly with a negligible steady state error.

This controller rejects the load disturbance very rapidly with no overshoot and with a negligible steady state error more than the classical sliding mode controller and the PI controller which is shown clearly in fig. 12.

Fig. 10 and 11 show a comparison between the classical field oriented control using PI controllers, the sliding mode current controllers and which based on fuzzy sliding mode current regulators. It shows clearly that the decoupling control is more maintained for the fuzzy sliding mode design than which obtained by a classical sliding mode and PI currents controllers.

The simulation results show that the proposed scheme gave satisfactory performances thus judges that the controller is robust.

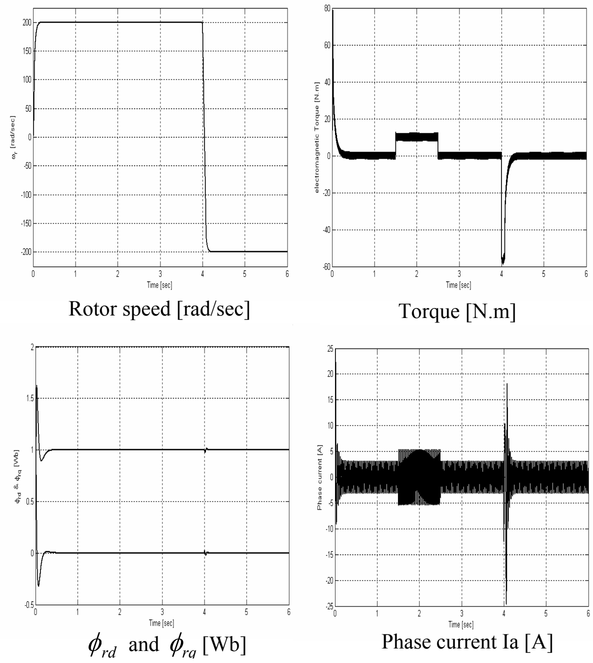

Fig. 9. Simulated results of fuzzy sliding mode speed and currents control of induction motor

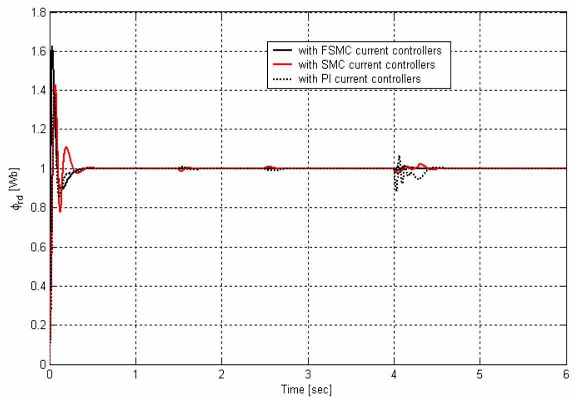

Fig. 10. Simulated results of the comparison between the decoupling obtained by PI, SMC and FSMC for IM.

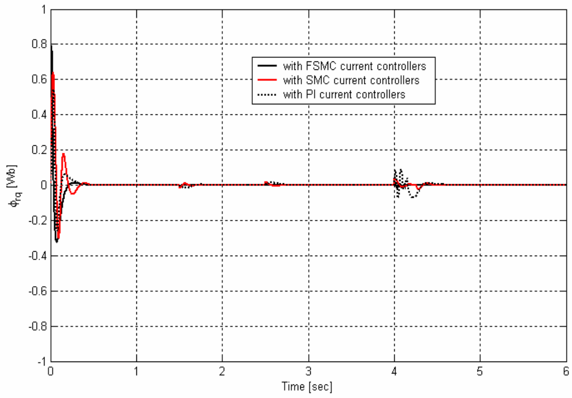

Fig. 11. Simulated results of the comparison between the decoupling obtained by PI, SMC and FSMC for IM.

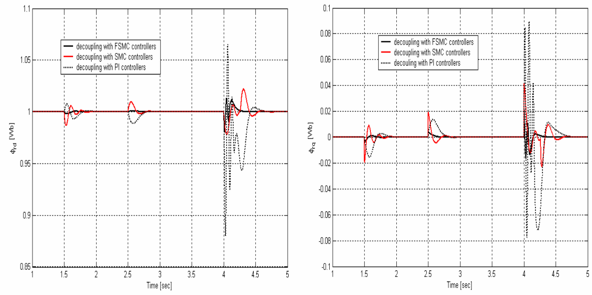

Fig. 12. Zoomed responses of decoupling obtained by PI, SMC and FSMC for IM.

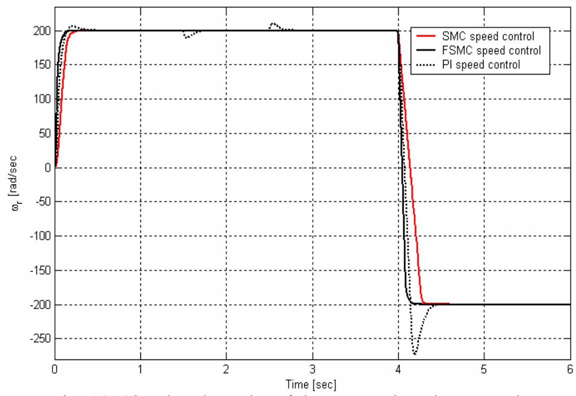

Fig. 13. Simulated results of the comparison between the PI, SMC and FSMC speed control of induction motor

VI. CONCLUSION

In this work, we have presented a fuzzy sliding mode controller for speed and currents control of induction motor. This study has successfully demonstrated the design of the fuzzy sliding mode for the speed control of an induction motor and the indirect field orientation control design based on fuzzy sliding mode control combination. The Proposed scheme has presented satisfactory performances (no overshoot, minimal rise time, best disturbance rejection) for time-varying external force disturbances. The simulation results obtained have confirmed the excellent decoupling maintain and the efficiency of the proposed scheme. Finally, the effectiveness of the PI, classical sliding mode with boundary layer controller and the fuzzy sliding mode controller has been verified through simulation.

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